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ELECTRO-OPTIC PERFORMANCE OF PLZT LENSES

Randall L. Lindsey, Second Lieutenant, USAF

September 1988

Final Report for Period October 1987 - February 1988

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USAF SCHOOL OF AEROSPACE MEDICINE
Human Systems Division (AFSC)
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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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The EDU-2/P PLZT Thermal/Flash Protective Device (TFPD) furnished to USAFSAM/RZV for testing and measuring the electro-optic performance yielded the following results: (a) switching delay time was 16 µs, average; (b) average time to achieve an optical density of 3.0 was 147 µs; (c) maximum optical density achieved was 4.1, corresponding to a .0079% transmission; (d) photopic and scotopic luminous transmittances were measured as 18.6% and 18.9%, respectively, in the "open" state. This report includes graphics illustrating all the results previously mentioned. In addition, two "best fit" functions were generated from the collected data which model the protective mode response of the PLZT Goggle to within a 0.249% RMS error.

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ELECTRO-OPTIC PERFORMANCE OF PLZT LENSES

INTRODUCTION

The EDU-2/P Flashblindness Goggle is a photo-protective device specifically designed to eliminate ocular damage from a nuclear flash. Each goggle lens is made of crossed polarizers sandwiching thin sheets of PLZT (lanthanum-modified lead zirconate titanate). A photodetector, mounted directly behind each lens, senses a high-intensity light flash (trigger event) and triggers the control circuit that applies a high voltage to the PLZT lens. With the high voltage applied, the lenses are in the "open" (transparent) state. If, at any time, the light level doubles in less than 100 μs, the control circuit will discharge the high voltage from the PLZT lenses, reducing the optical transmission to approximately 0.1%, corresponding to an optical density (OD) of 3.0. This rapid reduction of transmission is referred to as the switching response, and it occurs in less than 150 μs, with a resulting final transmission corresponding to OD 4.1, which is called the fully "closed" (opaque) state. The pretrigger light level is stored for future reference, and the lenses remain in the fully closed state for about 200 ms. The system then enters the servo mode, lasting approximately 25 s. During the servo mode, the control circuit increases or decreases the transmittance as necessary, maintaining a constant pretrigger light level throughput. If no other trigger events occur during the servo period, the controller returns to the pretrigger (nonservo) mode. However, if a trigger event does occur during the servo period, the system will re-trigger the lens, and the control circuit will begin the cycle again.

Brief History of the PLZT Goggle

In 1969 Sandia Laboratories, Albuquerque, New Mexico, achieved optical transparency in lead zirconate-titanate (PZT) ferroelectric ceramics by substituting moderate amounts of the element lanthanum in place of lead. This new material (PLZT) exhibited the quadratic (Kerr) electro-optic effect. Thus, the excellent optical qualities of these materials has allowed the practical utilization of their electro-optic properties in a number of devices. One of these devices was the Thermal Flashblindness Goggle.

In 1975 Sandia Laboratories began the design and development of PLZT Goggles for the U.S. Air Force to provide protection from temporary flashblindness and permanent retinal burns caused by the brilliant flash of a nuclear explosion. The EEU-2/P Thermal Flashblindness Goggle was the first goggle of this type produced. This goggle effectively protected the wearer from simulated nuclear flashes and showed great promise for future use. However, because of weight and operational constraints imposed by some aircrew members, such as KC-135 boom operators and pilots of high performance aircraft, the EEU-2/P goggle was not suitable. It was just too heavy and

bulky for the crewmembers comfort. Therefore, the newer EDU-2/P Thermal Flashblindness Goggle was developed. It exhibits the same functional characteristics as the EEU-2/P, but weighs much less and switches slightly faster.

Another proposed solution to solve aircrew fatigue from goggle use was to integrate the photo-protective material with the aircraft windshields. This was first tested and developed for use in the B-1 Bomber. The entire window from the side of the cockpit was made utilizing PLZT materials. The control circuitry was essentially the same as for the goggles, but modified to provide a higher voltage. Prototype tests showed the window responded slightly slower than the goggle, yet still provided ample protection against simulated nuclear flashes.

FUTURE USE

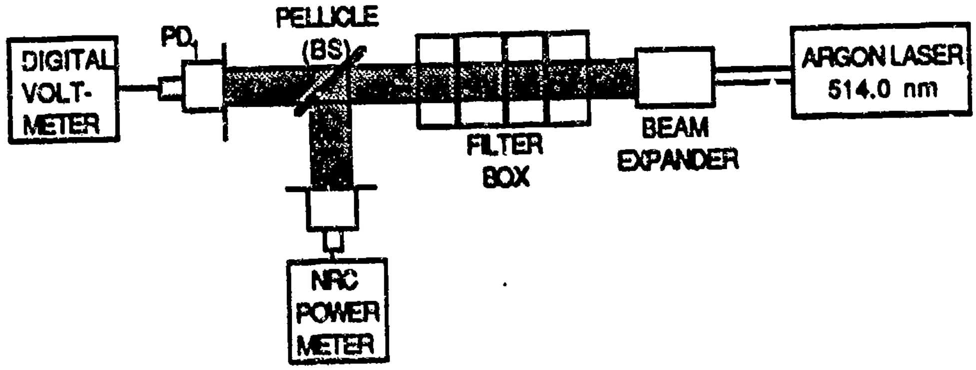
Currently, modifications are underway to improve the switching response of the electronic controller/PLZT lens combination. The modifications should shorten the activation switch time, improving the overall prformance of the material. Other uses of PLZT materials center on "fast switch" possibilities also. This "fast switch" frontier will focus on eye protection from exposure to fast/ultrafast laser pulses.

OBJECTIVE

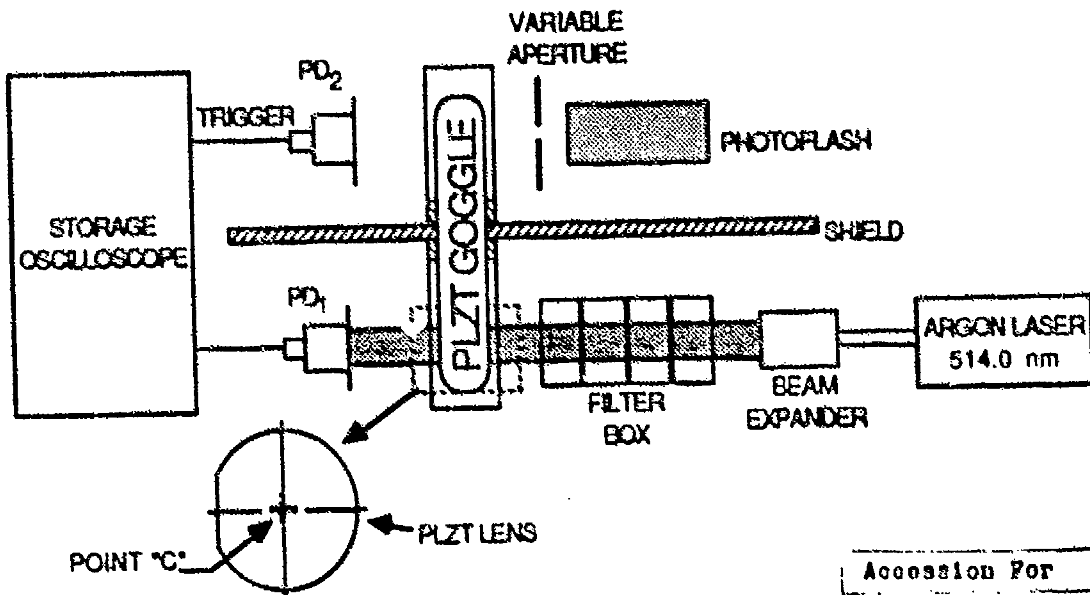
The objective of this study was to measure the optical density versus time response of the EDU-2/P Flashblindness Goggle, GP 10, serial number 003, to determine the effect activation and closure time have on protecting the eye from a nuclear flash.

METHOD

The experimental setup used to measure the electro-optic performance of the PLZT lenses is illustrated in Figure 1. A white light, xenon photoflash simulated the nuclear flash, and served as a trigger for both the PLZT lenses and the oscilloscope. A United Detector Technology (UDT) PIN 10 photodetector (PD) was used to measure the overall lens response to the flash. This particular PD was used because (1) its spectral response closely matched the spectral response of the PLZT lenses, and (2) it showed a linear response to an intensity increase of 4 orders of magnitude. A Spectra Physics 162A-07 continuous-wave (CW) argon ion laser operating at the 514.0 nm line was used as the monochromatic light source to the PD because its wavelength closely matched the peak spectral response of both the PLZT lenses and the PD. As shown in Figure 1B, the incident laser beam was aligned perpendicular to point "C" on the lens. The measured beam diameter at the PLZT lens and PD surface was 1.2 cm. The PD was calibrated using the argon laser and a Newport Research Corporation (NRC) power meter (Figure 1A details method). The PD calibration curve is shown in Figure 2, and Figure 2A is a best-fit model for the PD calibration curve. The laser power was adjusted by use of neutral density filters, and was set below the saturation point of the PD.



1A: PD CALIBRATION



1B: TEST SETUP

Figure 1. Experimental setup.

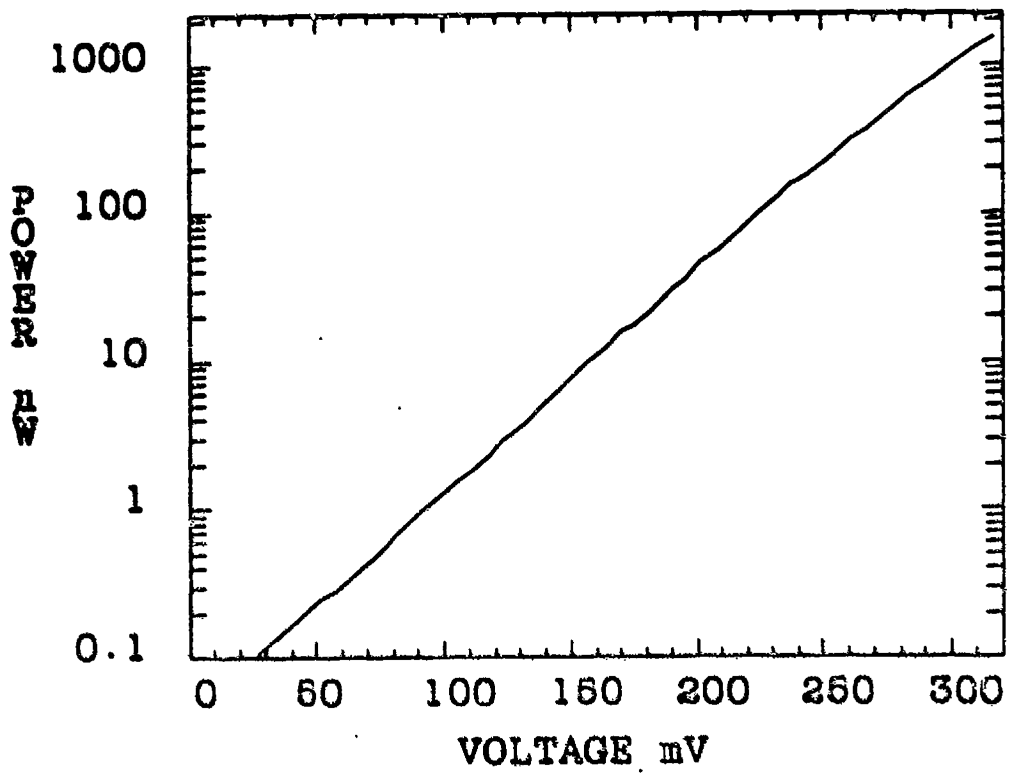


Figure 2. Photodetector calibration curve.

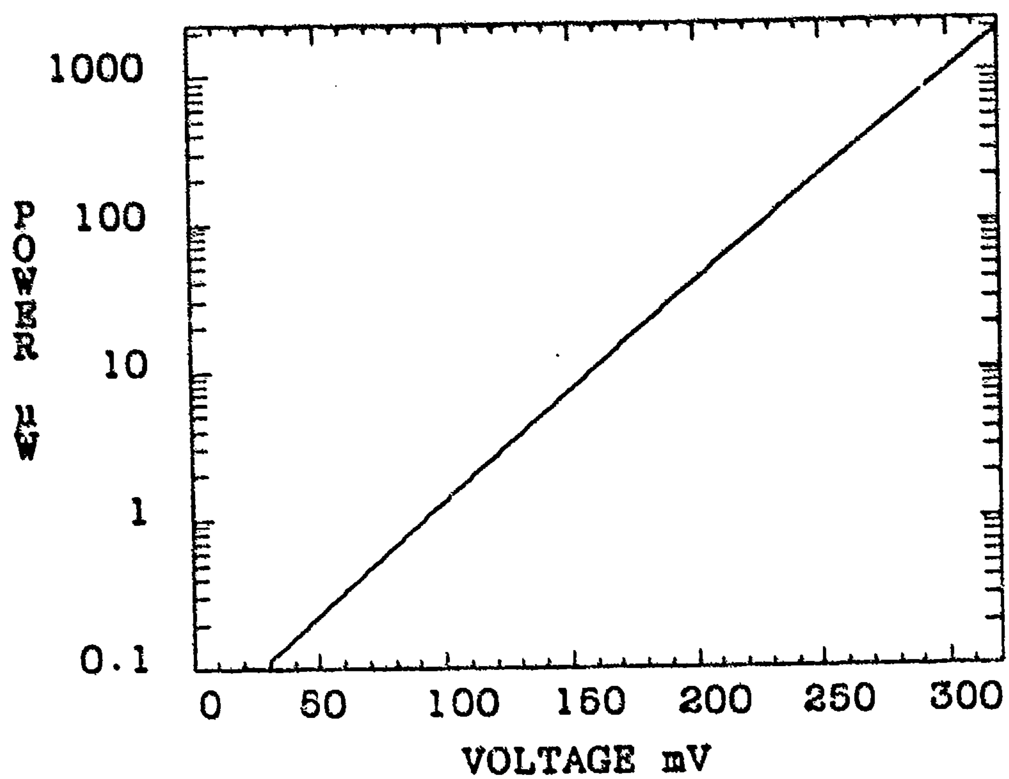


Figure 2A. "Best-fit" function for photodetector calibration curve
$y(x)=10\wedge(-3.96e\text{-}6*x^2 + 1.60e\text{-}2*x - 1.43)$

To measure the lenses switching response, the photoconductive PD was operated in the photovoltaic mode. This way, the PD gives a logarithmic output (millivolts) of an incident power (microwatts) ranging over four orders of magnitude (10^4). Therefore, the entire actuation response of the lenses could be captured in a single oscilloscope trace.

The procedure to capture the switching response was straightforward. With the lenses in the open state (voltage applied to the PLZT material, causing transparency), the amount of laser light incident on the PD was constant and below the saturation limit of the PD. Once PLZT closure began (activated by the trigger flash), the amount of laser light incident on the PD changed, and the oscilloscope recorded the changes in the PD output. The recorded trace was then digitized and saved for future reference and analysis.

Spectral analysis of the PLZT lenses was measured using the Perkin-Elmer Spectrophotometer. The spectral scan ranged from 200-1200 nm, in 1-nm increments. Figures 3A and 3B illustrate the spectral optical density as a function of wavelength, and Figures 4A and 4B illustrate the spectral transmittance as a function of wavelength. The photopic and scotopic transmittances were calculated by integrating and averaging the spectral transmittance over the entire visible region (400-700 nm), which corresponds to white light; those calculated values are shown in Figures 4A and 4B for the static-on and static-off states, respectively. Tables 1 and 2 list the optical density per visible wavelength for each static case. A detailed equipment list is presented in the Appendix.

DISCUSSION and RESULTS

The main objective of this study was to measure the optical density versus time response of the EDU-2/P Flashblindness Goggle to determine the effect activation and closure time have on protecting the eye from a nuclear flash. To achieve this objective, the following areas needed to be considered:

1) delay time from the onset of the flash (t0) to the time the protective-mode response of the goggles began
2) time from t0 to an optical density (OD) of 3.0
3) maximum OD achieved
4) response modeling
5) spectral response, to include transmittance.

In this report, time t0 is defined as the initiation time of the trigger flash used to generate the protective-mode response. Delay time $t\delta$ is defined as the time after t0 to the time closure is initiated. Delay time can also be referred to as trigger time. To eliminate possible delays and errors associated with the test equipment, the output of the photodiode which measured the response of the goggles was sent through a delay line. This method assured that the delay time was purely a function of the actual response of the goggles and not affected by transients which might be present in the associated test equipment.

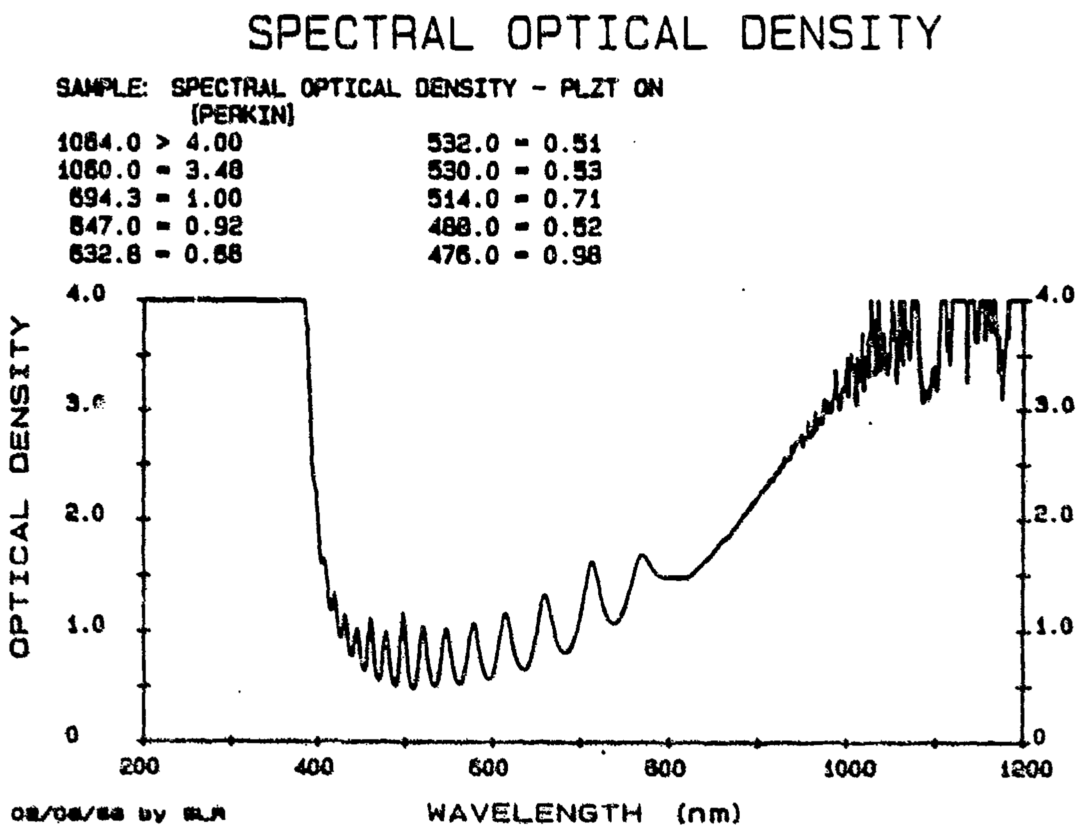


Figure 3A. Open state optical density of PLZT lenses as a function of wavelength.

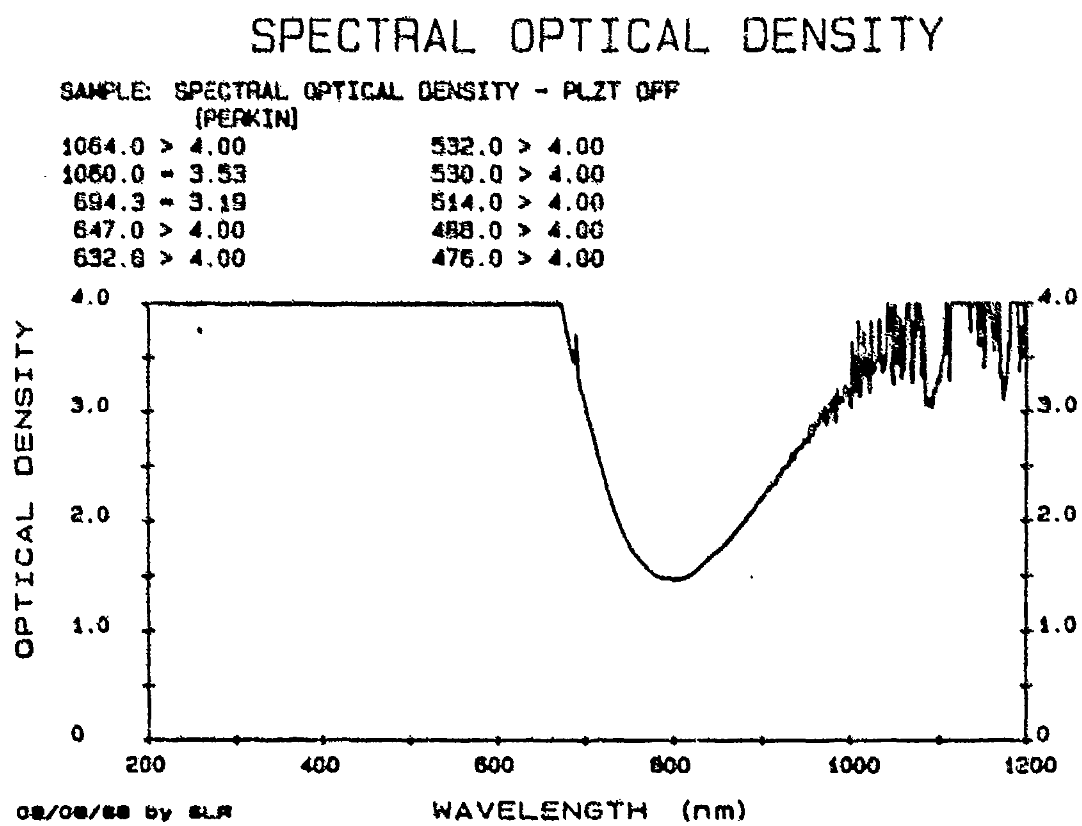


Figure 3B. Closed state optical density of PLZT lenses as a function of wavelength.

SPECTRAL TRANSMITTANCE

SAMPLE: SPECTRAL OPTICAL DENSITY - PLZT ON
(PERKIN)

PHOTOPIC LUMINOUS TRANSMITTANCE:	18.6%	Chromaticity Coord.:	
SCOTOPIC LUMINOUS TRANSMITTANCE:	18.9%		X = 0.304
MEAN UV TRANSMITTANCE:	0.0%		Y = 0.352
			Z = 0.344

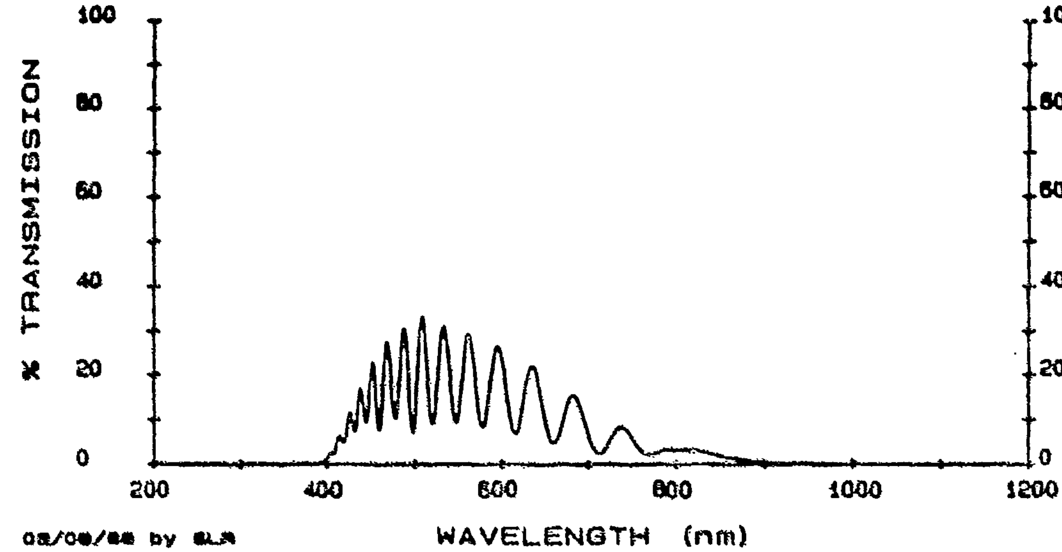


Figure 4A. Open state transmittance of PLZT lenses as a function of wavelength.

SPECTRAL TRANSMITTANCE

SAMPLE: SPECTRAL OPTICAL DENSITY - PLZT OFF
(PERKIN)

PHOTOPIC LUMINOUS TRANSMITTANCE:	0.0%	Chromaticity Coord.:	
SCOTOPIC LUMINOUS TRANSMITTANCE:	0.0%		X = 0.328
MEAN UV TRANSMITTANCE:	0.0%		Y = 0.262
			Z = 0.410

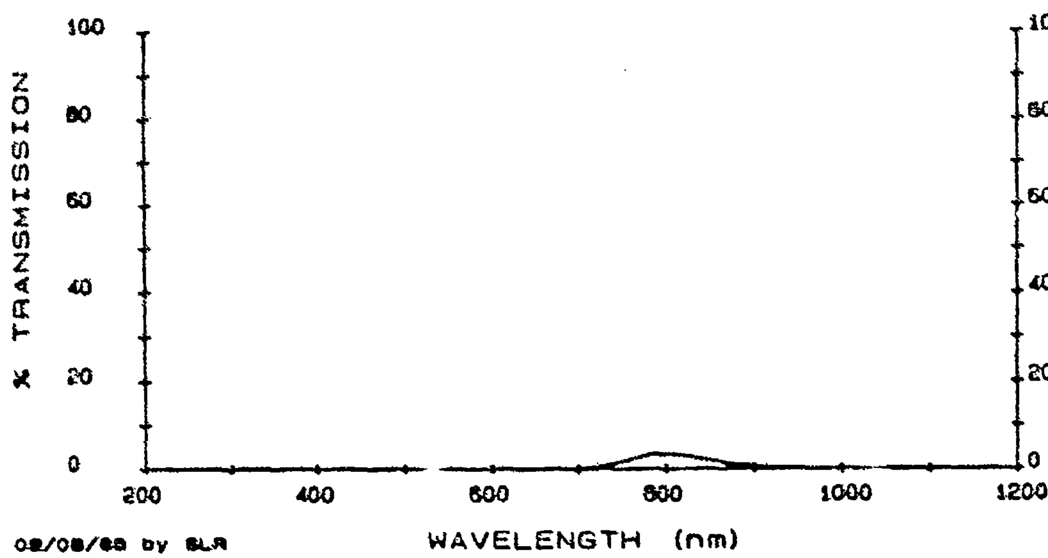


Figure 4B. Closed state transmittance of PLZT lenses as a function of wavelength.

TABLE 1. OPEN STATE SPECTRAL OPTICAL DENSITY OF THE PLZT LENS

Listed in Units of Optical Density

Wave	0	1	2	3	4	5	6	7	8	9
400	1.87	1.88	1.84	1.79	1.72	1.64	1.56	1.49	1.44	1.40
410	1.39	1.39	1.38	1.36	1.32	1.27	1.21	1.16	1.12	1.10
420	1.10	1.11	1.13	1.14	1.13	1.10	1.06	1.01	0.96	0.93
430	0.90	0.90	0.91	0.93	0.96	0.98	0.98	0.97	0.93	0.89
440	0.84	0.80	0.78	0.76	0.76	0.78	0.80	0.84	0.87	0.90
450	0.90	0.89	0.85	0.80	0.74	0.70	0.66	0.64	0.64	0.65
460	0.68	0.72	0.78	0.84	0.88	0.90	0.89	0.86	0.81	0.75
470	0.69	0.65	0.61	0.59	0.58	0.58	0.60	0.63	0.66	0.71
480	0.75	0.79	0.83	0.85	0.84	0.81	0.77	0.72	0.66	0.61
490	0.57	0.53	0.51	0.51	0.51	0.53	0.57	0.61	0.66	0.73
500	0.79	0.86	0.90	0.92	0.91	0.87	0.82	0.76	0.70	0.65
510	0.60	0.56	0.53	0.51	0.50	0.51	0.52	0.53	0.56	0.60
520	0.64	0.69	0.74	0.80	0.84	0.87	0.89	0.89	0.87	0.84
530	0.80	0.75	0.71	0.66	0.63	0.59	0.57	0.55	0.54	0.53
540	0.53	0.54	0.55	0.57	0.60	0.63	0.67	0.71	0.75	0.79
550	0.83	0.87	0.90	0.91	0.91	0.90	0.87	0.84	0.80	0.77
560	0.73	0.69	0.65	0.63	0.60	0.58	0.57	0.56	0.55	0.55
570	0.56	0.57	0.59	0.61	0.63	0.66	0.69	0.73	0.76	0.80
580	0.84	0.88	0.91	0.94	0.96	0.97	0.96	0.95	0.93	0.90
590	0.87	0.84	0.80	0.76	0.73	0.70	0.68	0.66	0.64	0.62
600	0.61	0.60	0.60	0.60	0.60	0.61	0.62	0.64	0.65	0.67
610	0.70	0.73	0.76	0.79	0.83	0.86	0.90	0.94	0.97	1.00
620	1.03	1.05	1.06	1.07	1.06	1.05	1.03	1.00	0.98	0.95
630	0.91	0.88	0.85	0.82	0.80	0.77	0.75	0.74	0.72	0.71
640	0.70	0.69	0.69	0.69	0.69	0.69	0.70	0.71	0.72	0.73
650	0.75	0.77	0.79	0.82	0.84	0.87	0.90	0.94	0.97	1.00
660	1.04	1.08	1.12	1.15	1.18	1.21	1.23	1.24	1.25	1.24
670	1.24	1.22	1.20	1.18	1.15	1.12	1.10	1.07	1.04	1.02
680	0.99	0.97	0.95	0.93	0.91	0.90	0.89	0.88	0.87	0.86
690	0.86	0.86	0.86	0.86	0.86	0.87	0.88	0.89	0.90	0.92
700										

TABLE 2. CLOSED STATE SPECTRAL OPTICAL DENSITY OF THE PLZT LENS

Listed in Units of Optical Density

Wave	0	1	2	3	4	5	6	7	8	9
400	5.00	4.22	5.00	5.00	5.31	5.00	5.00	5.00	5.04	5.37
410	4.42	4.94	4.98	5.00	5.48	5.77	5.00	5.00	5.00	5.02
420	5.69	5.00	7.00	5.00	5.23	4.68	4.92	5.00	5.00	5.00
430	5.20	6.26	4.64	4.68	4.83	4.55	4.52	4.72	4.27	5.01
440	4.32	5.35	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.13
450	5.00	5.00	5.00	5.00	5.34	7.03	5.83	4.62	4.45	5.10
460	4.10	5.28	4.15	5.00	5.79	5.11	4.99	4.57	4.46	4.49
470	5.54	5.00	5.00	5.00	5.37	5.00	4.29	5.00	5.00	5.00
480	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
490	5.00	4.55	5.62	5.46	5.01	4.54	4.07	4.92	4.62	4.38
500	4.18	4.89	4.57	4.88	4.86	4.59	4.25	4.39	4.77	4.28
510	4.11	4.57	5.00	5.00	4.71	5.00	5.00	5.00	5.00	6.14
520	5.00	5.00	5.00	5.00	5.23	5.00	5.00	5.00	4.61	5.07
530	5.00	5.00	5.00	5.00	4.56	5.00	5.00	5.00	5.00	5.14
540	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
550	5.00	5.00	5.00	5.00	5.18	5.00	5.00	5.00	5.00	5.22
560	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
570	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
580	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.27
590	6.69	5.00	5.00	5.00	5.00	5.00	6.35	5.00	5.00	5.09
600	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
610	5.00	5.00	5.00	5.00	5.00	4.66	4.22	5.00	5.00	5.00
620	5.00	5.00	5.00	5.00	5.10	4.49	5.00	5.00	5.00	5.00
630	5.00	5.00	5.31	4.68	6.64	5.00	5.00	5.00	5.00	5.00
640	5.00	5.00	4.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
650	5.00	5.00	5.00	5.00	4.78	5.00	5.00	5.00	5.00	5.02
660	5.47	5.00	4.23	5.00	5.33	4.36	4.70	3.99	5.62	4.44
670	4.43	4.08	4.20	4.18	3.95	3.99	3.97	3.85	3.85	3.96
680	3.73	3.81	3.66	3.60	3.67	3.52	3.60	3.45	3.53	3.40
690	3.48	3.41	3.39	3.36	3.33	3.26	3.24	3.22	3.18	3.15
700										

A separate analysis of the EDU-2/P Flashblindness Goggle was conducted by Honeywell Ceramics Center (#1) on 28 October 1987. In the analysis, tδ was 20 µs. These results compare nicely with our results, shown in Figures 5 and 6, where a typical delay time ranged from 13 to 18 µs from the onset of the test flash (t0).

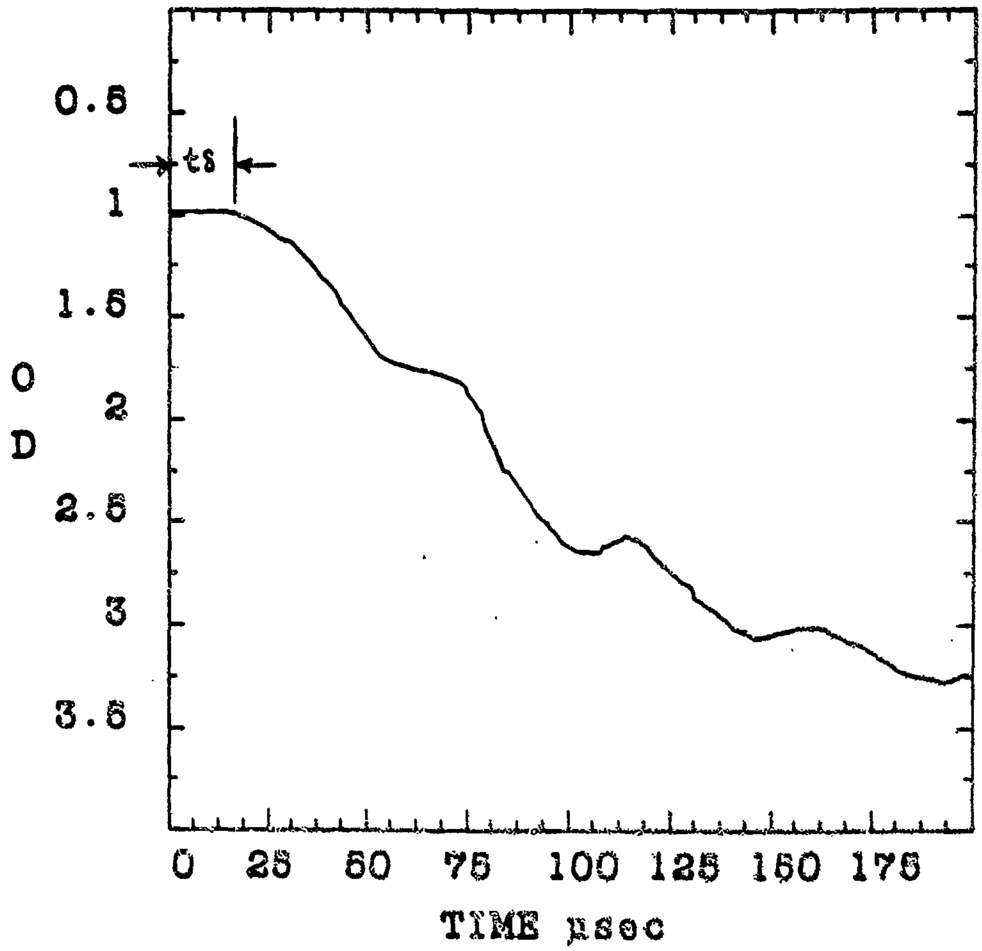


Figure 5. PLZT closure response characteristics. Time t0 is at 0.

Another important parameter considered was the time required to achieve 3.0 OD (an average transmittance of 0.1%). From Figure 6, 3.0 OD was achieved at about 147 µs. On consecutive runs, an OD of 3.0 was consistently reached at or below the 150 µs mark. The average transmittance was determined as illustrated in Figure 6 to account for oscillations around the 3.0 OD point.

The maximum density measured was about 4.1 OD. From Figure 7, this value was reached at about 8.0 ms, and remained at this level for a total of 200 ms from t0, as expected. Note that the response rapidly approached 3.5 OD and then flattened, approaching 4.1 OD at a much slower rate. This was an important characteristic in determining a modeling equation for the response.

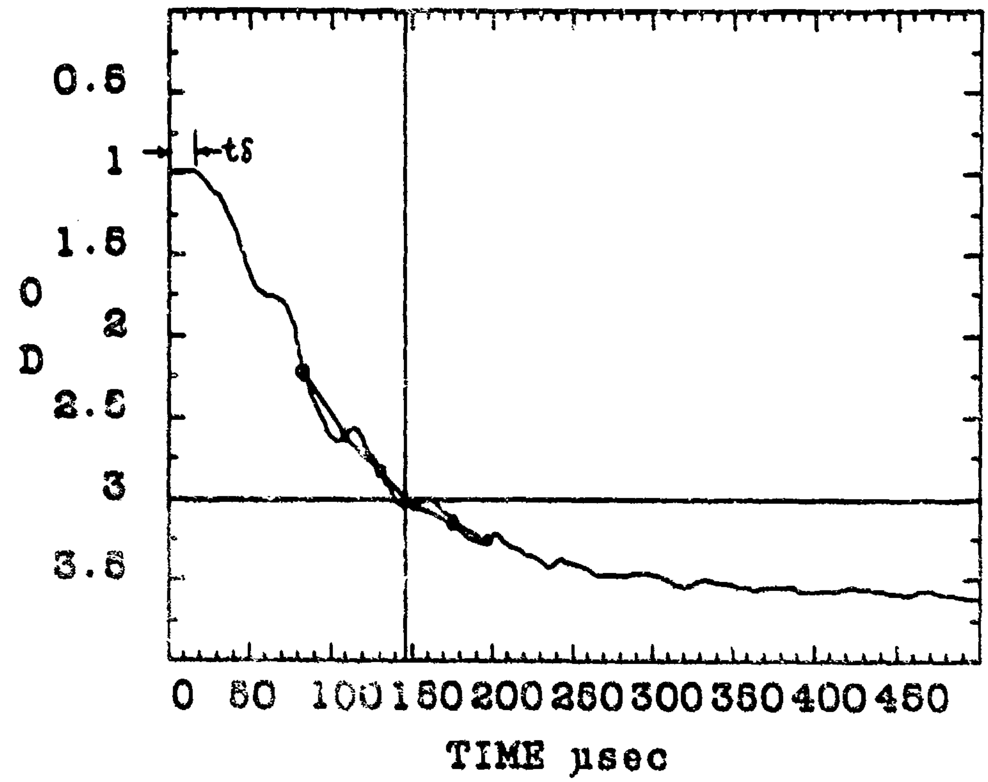


Figure 6. PLZT closure response characteristics. Delay time is measured from time 0 (t0). The cross-hairs indicate the time where the closure response reached OD 3.0.

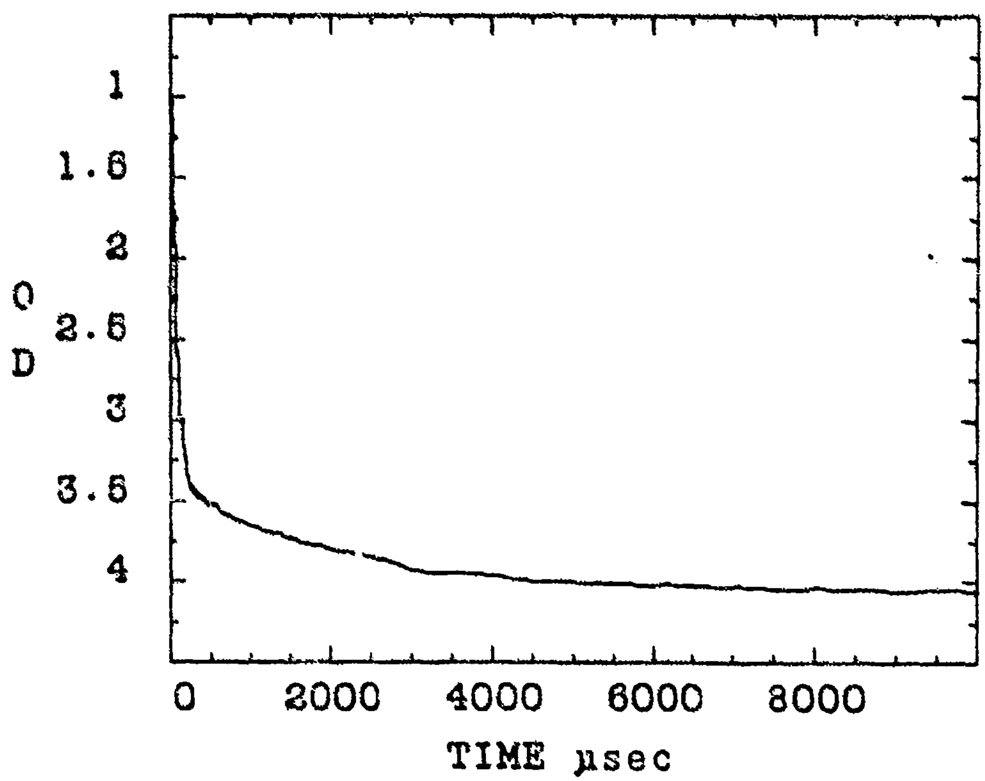


Figure 7. PLZT closure response. Response over "long" term.

To characterize the response of the PLZT Goggle, it was necessary to derive an equation which best fits the collected data. From a report prepared by Sandia National Laboratories (#2), the current controller can be modeled by a function of the type

$$i(t) = K(1-e^{-t/RC})$$

where

K = maximum discharged current
RC = time constant set by input network

This function was used as the initial model in a computer program (#3) that calculates a "best fit" function to a given set of data points. These "best fit" functions are shown in Figures 8, 9, and 10. The function illustrated in Figures 8 and 9 is the "smoothed" response function while Figure 10 illustrates the "oscillatory" response function. Both functions fit the original data to a Root Mean Square (RMS) error of about 0.249%.

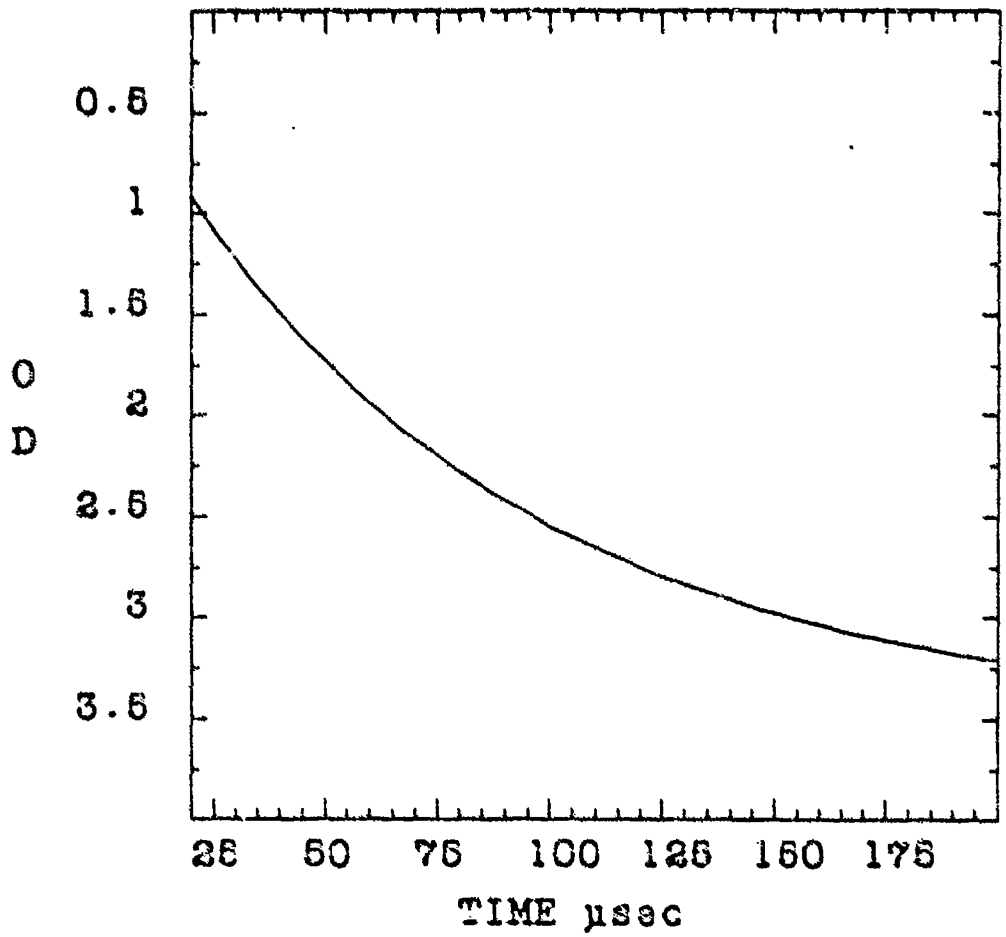


Figure 8. PLZT closure modeling function.

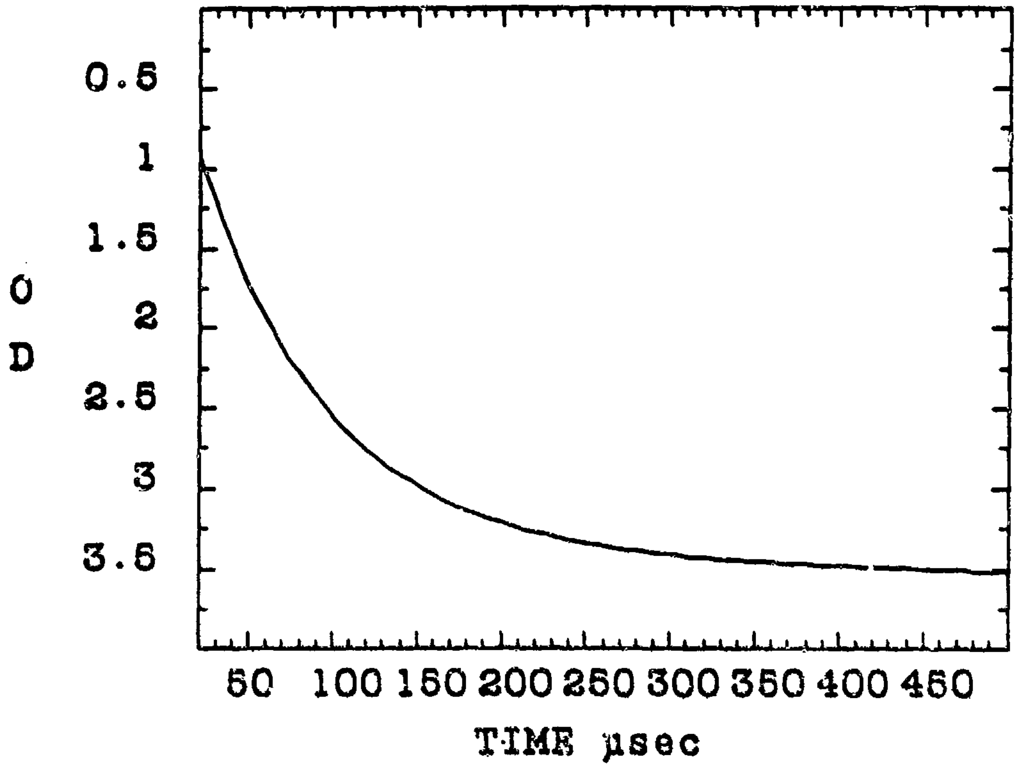


Figure 9. PLZT closure function modeling average closure response ("smoothed.")

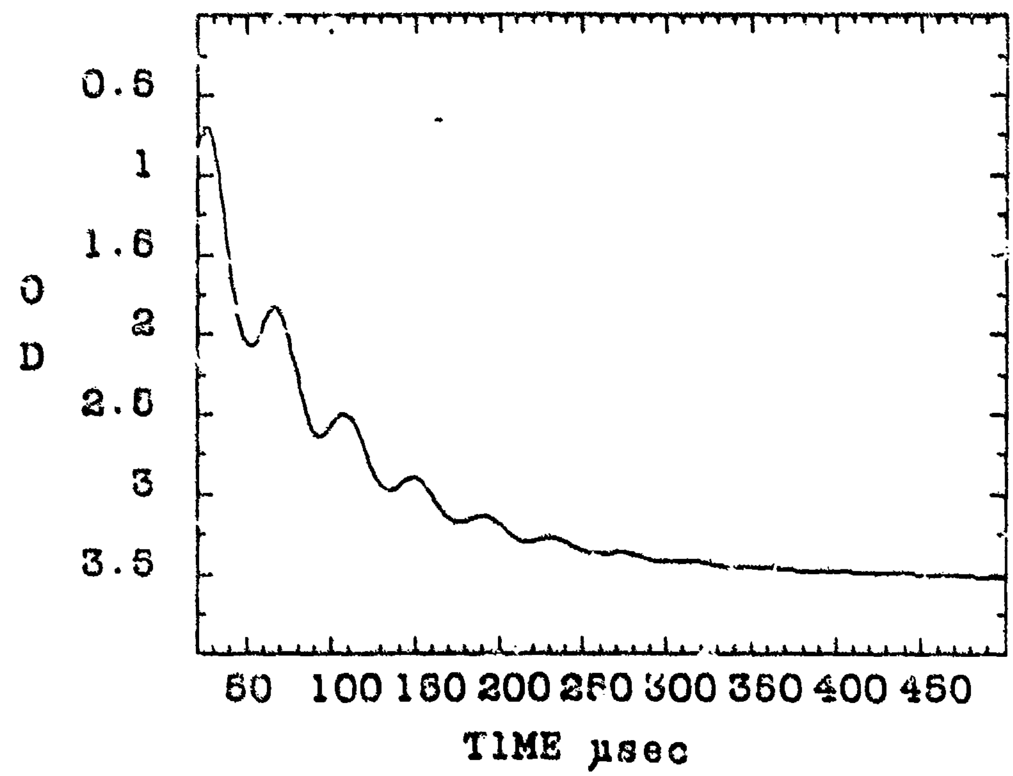


Figure 10. PLZT closure function modeling the oscillatory characteristics of the closure response.

Similar oscillatory characteristics as seen in the time response curves were also observed here in the spectral response (see Figures 3A and 4A). The spectral response of the PLZT goggles showed an increasing wavelength dependence between 400 and 800 nm. This OD modulation results from operating the PLZT material in the transverse birefringent mode (#4). Nevertheless, the photopic and scotopic transmittances were measured as 18.6% and 18.9%, respectively, in the static on case.

CONCLUSIONS

In conclusion, the EDU-2/P Flashblindness Goggles provided to USAFSAM/RZV for testing and measurement yielded the following results:

1. The delay time ($t\delta$) was measured as 16 μs, average.

2. The time to achieve OD 3.0 was consistently measured at 147 μs, average.

3. The maximum optical density was approximately 4.1 OD. The transmission stayed at OD 4.1 for 200 ms after t0. Then it exponentially increased, reaching a transmission of 18.9% (OD 0.72) 550 ms after t0 (350 ms exponential rise from OD 4.1).

4. The functions which provide the best fit to the actual data collected follow:

   a. "smoothed" (see Figure 9)

$$f(t) = Ae^{-t/\tau} + Be^{-t/T} + C$$

where A=3.226, B=0.6898, C=-4.1, τ=77.501, and T=2811.3

   b. "oscillatory" (see Figure 10)

$$f(t) = [A + D\cos(\omega t + \psi)]e^{-t/\tau} + Be^{-t/T} + C$$

where D=0.6306, ω=0.1523, and ψ=1.895

5. Spectral analysis showed an optical density of 0.71 at 514.0 nm in the normal operational mode with photopic and scotopic luminous transmittances of 18.6% and 18.9%, respectively.

The functions generated from the data (Figures 8, 9, and 10) will simulate the protective-mode response of the EDU-2/P Goggle very nicely, assuming that the trigger delay ($t\delta$) is about 20 μs, which means that these functions should be used to model the goggles response only after 20 μs. Notice that Figures 8, 9, and 10 display the functions starting from 20 μs. This delay accounts for the lag response between the initial

detection of the flash by the photodetector and the actual discharging of the PLZT lens by the controller circuit.

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APPENDIX

TABLE A-1. EQUIPMENT LIST

MANUFACTURER	DESCRIPTION	SERIAL #
1. Spectra-Physics	Mod 162A-07 Argon Laser	12366/5864
2. Tektronics 7834	Storage Oscilloscope	B047071
3. Newport Research Corp	Power Meter	
4. United Detector Tech	PIN-10D Photodetector	425,2031
5. GP 10 EDU-2/P	Flashblindness Goggle	003
6. Ealing Corp	Neutral Density Filters	Set M
7. Melles Groit	10X Beam Expander	
8. Tektronics C-53	Oscilloscope Camera	B097179
9. Beckman Instruments	Digital Volt Meter DM25	40425277